PB -229 232

WATER QUALITY CRITERIA FOR AQUATIC LIFE

Clarence M. Tarzwell

Robert A. Taft Sanitary Engineering Center
Cincinnati, Ohio

1957

DISTRIBUTED BY:

NTIS

National Technical Information Service
U. S. DEPARTMENT OF COMMERCE
5285 Port Royal Road, Springfield Va. 22151

PB 229 232

WATER QUALITY CRITERIA FOR AQUATIC LIFE

BY

CLARENCE M. TARZWELL

A Separate from Biology of Water Pollution: Transactions of the Seminar on Biological Problems in Water Pollution held at the R. A. Taft Sanitary Engineering Center, April 23-27, 1956.

U. S. DEPARTMENT OF HEALTH, EDUCATION, & WELFARE

1957

Reproduced by
NATIONAL TECHNICAL
INFORMATION SERVICE
U S Department of Commerce
Springfield VA 22151

PB.229232

Reproduced from best available copy.

WATER QUALITY CRITERIA FOR AQUATIC LIFE

Clarence M. Tarzwell
Chief of Aquatic Biology
Robert A. Taft Sanitary Engineering Center
Public Health Service
Cincinnati, Ohio

The lakes and rivers of North America have played a very important role in the opening and development of the continent. In our Great Lakes we have a fresh water resource far surpassing any other in the world. Our rivers and hundreds of thousands of inland lakes are outstanding in their many uses and support a diversity of the most valuable fishes to be found anywhere. Perhaps it is because of this great wealth in aquatic resources, which many considered to be inexhaustible, that we have been so remiss in their protection and conservation. Their importance is only now coming to be generally appreciated. The great increases in population since 1900 and the manifold increases in the volume and variety of water uses have shown that in some areas the supply of water is definitely limited. As with other resources we find that value varies directly with demand and inversely with supply. In the western areas which recently suffered from a severe drought it was found that when local drinking water supplies dry up,water will be purchased at any necessary price, however high it may be.

What is true for drinking water is also true in some measure for aquatic life resources. We have already found that as the demand for desirable fishing increases and the supply diminishes, the amount paid for such recreation becomes greater. The development of the country has drastically reduced or eliminated fishing waters in extensive areas. Deforestation, fire, overgrazing, and unwise agricultural practices have increased surface runoff and decreased seepage causing floods, intermittent flow, the drying up of springs, erosion, silting, and the filling of stream beds. Removal of streamside vegetation has promoted bank erosion, the widening of streams, and warming of the water. Industrial and other pollution has blocked fish migration and has rendered many areas unsuitable for fish. These practices which alter or destroy the aquatic habitat are the chief cause of the decline of aquatic life resources. The surest way to eliminate a species or group of species is to destroy their habitat or produce environmental conditions unfavorable for them. The only way to maintain a species is to protect and maintain environmental conditions essential for and conducive to its growth, reproduction, and well being.

Protection and conservation of aquatic life is not a simple task. Some have questioned its value and feasibility. Our fisheries are now an important resource. The commercial fisheries of the United States and Alaska have an annual production of almost five billion pounds (1). This crop represents a high protein resource which can be expected to increase in value. While commercial fisheries utilize a great deal of equipment and employ large numbers of people, their economic worth is only a fraction of that of sport

fishing. In 1955 there were more than 17 million licensed fisherman in the United States. There are several million additional fisherman who fish in the Great Lakes and in marine waters where a license is not required. According to the National Survey of Fishing and Hunting (2), sport fishing in the United States has an annual value of almost two billion dollars. Within the next 100 years the number of fishermen and the value of the fishery will increase severalfold if the resources can be preserved.

In comparing the beneficial uses of a stream, there has often been a tendency to underestimate the wildlife and recreational values and to take a short rather than a long view. When evaluating our fisheries resources we should consider the returns not just for one year but over the centuries because these resources are renewable. The aesthetic, recreational, and health values of our waters are difficult to measure, but they are great. The recreational industry is a large one and is expanding every year. In a few states it is the first ranking industry and in many others it is of considerable importance. In the industrial state of Michigan it is reputed to rank second. As our population increases there will be an ever growing demand for and use of our forests, parks, preserves, wilderness areas, and streams, where people can engage in water sports and "get back" to nature and relax. It is believed that our aquatic life resources and the aesthetic value of our lakes and streams, which are largely inseparable, are well worth our earnest and sincere efforts to preserve them.

The objective of water quality criteria for the protection of aquatic life is to preserve or restore environmental conditions essential for its growth, reproduction, and well being. If these requirements are known and understood, criteria can be set up which will achieve this objective. If habitat requirements are not fully known, criteria can only be based on the best information available and changed whenever the need is indicated by new information.

Under our present state of knowledge a suitable water cannot be defined in chemical terms alone. There are several reasons for this situation. Different species of fishes and the organisms in their food chain vary widely in their sensitivity to dissolved materials. We do not know the effects on aquatic life of various concentrations of many materials individually or in combination. Mixtures of materials often have effects different from those of the individual components. Further, we do not know minimal lethal levels for many materials or their mixtures, nor do we know the most favorable concentrations of materials essential for the organisms. Perhaps the best definition that can be given of a suitable fish habitat is -- "A suitable fish habitat is one which produces a satisfactory fish crop." The adequacy of a fish crop is judged by its quality and the pounds produced per unit of surface area. Commonly, productivity and suitability are judged by catch per unit effort, growth rate, condition factor, quality of the flesh, and the size and species composition of the catch. In fisheries management an effort is made to manipulate the environment so that conditions are made more favorable for the desired species and less favorable for those not wanted.

> The report includes general discussion of environmental factors; settleable solids and turbidity; pH; Dissolved oxygen; carbon dioxide; Dissolved solids; chlorides; fluorides; Toxic materials; and a summary. <

While our knowledge of the habitat requirements of fishes is far from complete, enough information is now available so that some criteria and procedures can be set up which will be of value in the maintenance of a satisfactory environment and production of a suitable crop. However, much research is still needed to obtain all the information essential for the solution of this problem.

The environmental requirements of fishes may be roughly grouped under four main headings, (1) a favorable water supply; (2) suitable spawning facilities; (3) an adequate food supply for all age groups; and (4) good pools and shelter. In the abatement and control of pollution we are chiefly concerned with the first requirement, a favorable water supply. Natural waters have widely varying physical and chemical properties. The suitability of any water for fish life depends on its quantity, permanency, and quality; that is, its temperature, the concentration of dissolved atmospheric gases, salts and other minerals, and suspended solids.

As here used water pollution is the addition of any material or waste to a water in such quantities that it interferes with, lessens, or destroys a beneficial use. In this regard perhaps the simplest definition of pollution is "too much." For example, if "too much" is not added, the discharge to a stream of organic matter such as sewage has a fertilizing effect which is beneficial to fish production. However, when the capacity of the stream to utilize organic materials is exceeded so that unfavorable environmental conditions are produced and a beneficial use is damaged, such a discharge becomes pollution. It is evident, therefore, that water quality criteria for the protection of aquatic life must entail some quantitative measurements. Before criteria can be set up we must know or have some measure of how much is "too much" for those species we wish to protect at all stages in their life history and in waters of different quality. These criteria must insure environmental conditions favorable to all life activities and to general well being--mere survival is not enough. These environmental factors will be discussed in some detail.

Environmental Factors

Temperature

As a group, aquatic animals of the temperate zone are adapted to fluctuations in temperature between 39° and 90°F. Not all can withstand this range and some can withstand higher and some lower temperatures for a time. The range of temperature which can be tolerated by different species varies considerably as does their ability to withstand sudden changes or to acclimate themselves to unusual temperatures. Each species has a preferred range of temperature within which it does best and a zone above and below this in which it can survive for short periods. Proper acclimatization enables certain species to survive at temperatures which would be fatal under conditions of sudden exposure.

Fish have a rapid rate of adaptation to high temperatures (3) but adaptation to lower temperatures proceeds at a much slower rate. When suddenly exposed to higher temperatures fish can withstand much higher temperatures in summer than in winter. As the summer season develops, changes in upper lethal temperatures reflect the major changes in water temperature, rising with ascending temperatures and falling as the water cools in the fall. Brett (3) reports that the lethal temperatures for the bullhead rose from 29.1°C. on May 12 to 35.3°C, by July 8. Brett (4) also found that there is a considerable difference in the time required for completion of acclimation with respect to heat tolerance at each level of temperature. It has been shown that some species exhibit geographic differences in their resistance to high temperatures while others do not (5). The writer noted a bass kill in a southern Michigan lake in June 1936 when the water reached 94°F. during an unusually hot period. However, a temperature of 96°F. in Wheeler Reservoir in 1938 appeared to have no lethal effects. The difference may have been due to a different acclimation history. It was observed that a temperature of 108°F. killed all the fish in a pond near Savannah, Georgia, in 1945. Allowable peak temperatures brought about by some unnatural cause may, therefore, be somewhat different in different portions of the country, increasing from north to south.

Members of the family Salmonidae are cold water forms. Brook trout seem to do best in streams, the summer temperatures of which range between 52 and 68°F. (6) (7). While trout can survive much higher temperatures for short periods, streams having such temperatures are not first class trout streams. The writer found brown and rainbow trout surviving a peak temperature of 83°F. in the South Branch of the Pere Marquette River of Michigan in 1930. Brook trout survived peak temperatures of 81° and 82°F. in the East Branch of the Black River on successive days in July 1931. Fry (8) reported the upper lethal temperature for young brook trout (12 to 14 hours exposure) to be about 77.5°F. Such high temperatures are more favorable for minnows and suckers which increase greatly in numbers and compete for food and space with the trout (9). The result is that trout comprise a very small portion of the total fish population of the stream and supply little fishing even though the overall productivity of the stream may be great.

Four fish population studies made in the East Branch of the Black River of Michigan indicated that trout made upon only 9.6 percent of the total number of fish taken in the study areas. In the neighboring Pigeon River, another stream having temperatures above 75°F., trout comprised 15 percent of the total fish population in the areas counted (9). In a nearby cold stream, the West Branch of the Sturgeon River, trout represented 96 percent of the total population. In trout streams having high peak summer temperatures, suckers and minnows comprise the bulk of the fish population. Thus, while temperatures higher than the optimum and high temperatures of short duration (75° to 82°F.) may not kill trout, they produce environmental conditions more favorable for the coarse fishes, which increase at the expense of the trout population. This fact must be taken into consideration in

the establishment of temperature criteria for the cold water species. Such criteria must be based on optimum conditions and not on temperatures tolerated by trout. It is believed that for good trout production in streams subject to invasion by coarse species, temperatures should not exceed 68°F.

Since deforestation, overgrazing, unwise land use, removal of stream-side shade, and erosion have already caused the warming of streams to such an extent that the amount of trout water has been seriously reduced, and since trout fishing is in highest demand, it is believed that no wastes of significant heat content should be discharged into a trout stream if the stream is to be maintained for trout.

Favorable temperatures are especially important at spawning time for both cold and warm water species. It is well known that bass spawn in the spring when the water temperature exceeds 60°F. If the water is unnaturally warmed to this temperature for a period, spawning may be induced too early in the season. Then if waste discharges are discontinued over a weekend, water temperatures may drop into the 50's with the result that guarding males leave the nests, the eggs are infested with fungi, and no young are produced. Fluctuations of water temperature above and below 60°F. during the spring are detrimental to bass production.

A change in water temperature may affect the aquatic fauna directly or indirectly. While the change may be within the thermal tolerance of the fish, it may so alter environmental conditions that they become unfavorable for essential food organisms and certain life history stages of the fish, or the change may make them more favorable for competitors or predators. Temperature changes will directly affect the metabolic rate, growth, and reproductive processes. They may result in increased or decreased food production, interfere with spawning, or change an important part of the fauna, thereby altering the quantitative makeup of the population.

Although high summer temperatures have been considered of outstanding importance because of their possible lethal effects, it is believed that unnaturally high winter temperatures may be equally important. In the temperate zone the aquatic biota have evolved under conditions of quite wide differences in seasonal temperatures. For example, the eggs of some daphnia have to be chilled or frozen before they hatch. Many other organisms go through resting stages or specific stages of development at certain seasons. Some of the diatoms, for example, are abundant only at temperatures below 50°F. Other forms appear only at certain times of the year and there is a succession of forms with the seasonal changes. At present we have little conception of the changes which might be brought about by permanently elevating stream temperatures. A large portion of the biota might be changed and the whole food chain disrupted. For this reason consideration should be given to upper temperature limits during the winter season. This consideration may require increasing attention as the atomic energy industry develops. Temperature should not be raised to levels that induce spawning at unnatural times if there are periodic drops in temperature, and they should not be such

that they interfere with the development of important organisms in the fish food chain. Considerable study is needed before this problem can be approached intelligently.

Waters of significant heat content should not be discharged into a stream in such a manner that they create a temperature block across the stream. Further, an abrupt change of more than 9°F. may affect fishes adversely even if of short duration.

For a well rounded warm water fish population in the Ohio valley area it is believed that peak summer temperatures should not exceed 93°F. at any time or place. In the south such peak temperatures probably should not be above 96°F. This means that in general temperatures will be considerably below these levels. While several species can withstand higher temperatures (100° to 103°F.) for very short periods, 93° and 96°F. represent critical levels for most species in the designated areas. Further, while fish may, through certain adaptations, survive abnormally high temperatures for short periods, they cannot complete their life history at such temperatures. For good production, therefore, temperatures within a favorable range are required.

Settleable Solids and Turbidity

Studies carried out in connection with trout stream improvement investigations in Michigan indicated that sand bottoms are almost barren of benthic organisms and that the addition of sand or silt to rubble or gravel bottom streams greatly decreases stream productivity (9) (10) (11). In fact, shifting sand in quantities so small as to be unnoticed by casual observation can decrease the production of macro-invertebrates by drifting into the spaces between the gravel and thereby decreasing the areas for attachment and cover. It is believed that no inert inorganic, sandy, or other similar wastes should be added to a rubble, gravel bottom stream as such deposition may not only decrease the supply of desirable stream bottom insects but also seriously limit spawning of most nest-building fishes. Studies of the effects of mining wastes in California have shown that salmon select clear water for spawning and that the deposition of silt results in smothering of the eggs (12). Quantitative bottom samples taken in a series of similar streams in California showed that the average number of food organisms was always less in mined areas when inert inorganic materials were discharged to the stream than in nonmined areas (13). On the Scott River, samples from the silted area averaged 36 organisms per square foot, whereas those from the clean stream bottom above the mine averaged 249 per square foot, or 7 times as many. Similar studies (14) have shown that hydraulic mining wastes are detrimental to salmon and trout production. These and wastes from placer mining and from stamp mills and washing operations may completely choke a stream causing it to flow in a shallow sheet over the accumulated deposits. Further, debris dams created by such operations can eliminate the salmon by blocking migration.

From results of studies in various parts of the country, it is apparent that erosion silt is a major stream pollutant and that it produces

environmental conditions unfavorable for the reproduction and growth of fishes. Since the character of the stream and its bottom are of prime importance in determining the harmful effects of erosion silt, it is not possible to establish numerical criteria for settleable solids which are universally applicable. In some streams considerable amounts do very little additional harm, while in gravel rubble bottom streams even small amounts, as has been noted, reduce food production and limit spawning. It is believed that criteria on settleable solids should be established to protect environmental conditions in the stream, though they will vary from stream to stream, depending on local conditions.

Turbidity is usually due to solids which settle out slowly or to colloidal materials which may remain in suspension over long periods. The studies of Irwin (15), Wallen (15A), and others at Oklahoma A and M have shown that turbidity must be very high before it exerts a directly harmful effect on fishes. In some tests (15) direct reactions to turbidity did not appear until it reached 20,000 p. p. m. and for one species not until it reached 100,000 p. p. m. Most individuals of all species endured exposure to more than 100,000 p. p. m. for a week or longer but finally died at turbidities of 175,000 to 225,000 p. p. m. Fishes which succumbed to these turbidities had the opercular cavities and gill filaments clogged with silty clay particles.

In Oklahoma, Buck (16) carried on pond studies to determine the effects of turbidity on growth rate. At the end of two growing seasons the average total weight of fish in clear ponds was about 1.7 times that of those in ponds of intermediate turbidities and approximately 5.5 times greater than those in muddy ponds. Of the three species used, large mouth bass were most affected by turbidity. The effect on plankton production was even more striking since the average volume of net plankton in clear ponds during the 1954 growing season was 8 times greater than in ponds having intermediate turbidity and 12.8 times greater than the yield in most turbid ponds. However, catfish survived better in muddy ponds. Game fish feed by sight and in turbid waters they are at a disadvantage when competing with such fish as carp, buffalo, and carp suckers which employ a vacuum cleaner type of feeding. Turbidity can, therefore, bring about a quantitative and qualitative change in the fish fauna. In addition, metallic or sharp particles may kill fishes by causing abrasive injuries to the gills or by clogging the gills and respiratory passages.

Suspended solids and turbidity prevent light penetration, decrease photosynthesis, and thus limit algal production. Since algae are the basic material in the food pyramid, turbidity adversely affects fish production in an indirect manner. In most streams settleable solids and turbidity are largely due to soil erosion. Until erosion is brought under control, little can be done toward clearing up the streams. Reduction of turbidity is a difficult and long time problem which must be carried out in cooperation with soil conservation, agricultural, and forestry interests. In the meantime, however, efforts should be made to control or eliminate other sources of settleable solids and turbidity. Lagooning can be effectively used to remove settleable solids and turbidity from many wastes. Such procedures are

essential on all clear streams and they should be initiated in conjunction with efforts to reduce turbidity and settleable solids through control of soil erosion.

Turbidity standards must be somewhat local in their application as they will depend on the area and type of stream. It is possible to set up relatively simple turbidity standards which can be readily checked for compliance by field tests. Turbidity standards might state that a certain percentage of the incident light at the surface shall reach a stated depth between 11:00 A. M. and 1:00 P. M. The depth selected would depend on the depth to which the regulatory agency felt the photosynthetic zone should extend. Different types of water differ in their capacities to absorb light. Water transparency is affected by the suspended matter, including the plankton, and by stain or color. In water of the clarity of usual municipal supplies, 9.5 percent of the solar energy present at the surface reaches a depth of 6 feet. Born (39) states that the limit for growth for the higher aquatic plants lies between 2.5 and 3.5 percent of the total surface energy at bottom depth, but that it rapidly declines below 4 percent where severe etiolation occurs in submerged seed plants. There is some evidence that certain algae can grow at levels of 1 percent of the incident light, but it is not definitely known how much light is required for them to produce more oxygen by photosynthesis than they use in their respiration. While criteria will vary with the area they can be kept relatively simple. For example, a criterion for a particular area might state -- under conditions of brilliant sunlight at or near noon 4 percent of surface incident light shall reach a depth of 6 feet. Incident light and light at any given depth can be readily read by means of a photometer fitted for underwater use.

pH

The pH of a water may exert a direct effect on fish if it is very high or very low due to strong bases or mineral acids. It may have an indirect effect through its influence on the toxicity of certain materials such as HCN, H_2S, ammonia, heavy metals, etc. Longwell and Pentelow (17) found that the toxicity of NaS solutions to brown trout was influenced markedly by variations in pH, the toxicity increasing as the pH became lower. The heavy metals are considerably more toxic at lower pH levels probably because they are more soluble. Ammonia becomes rapidly more toxic as the pH is raised above 8.2. The toxicity of a number of weak inorganic and organic acids, including hydrocyanic, hypochlorous, hydrosulfuric, carbonic, and tannic, is increased by lowering the pH.

Extreme pH values of 4 and 10 or slightly above have been tolerated by resistant fishes in certain areas. Some levels at which fish have been killed experimentally are: trout, 9.2; bluegills, 10.5; roach, pike, carp, and tench, 10.4 to 10.8. Fish mortality has been observed within a few hours at pH levels of 3.4 to 4. However, certain fish have been acclimated to live for considerable periods at pH levels as low as 4.5 to 4.2.

Studies of acid bog lakes (18) have shown that yellow perch, brown bullhead, bluegill, and pike can live at a pH of 4.4. Ellis (19) states that the pH of streams generally ranges between 7.4 and 8.5 with an overall range of 6.6 to 9.0, while bog streams and lakes vary from 4.0 to 6.8. He states that in most uncontaminated freshwater streams pH values range from 6.5 to 8.5.

Sudden or wide fluctuations in pH are undesirable. While fish can withstand pH levels as high as 9.5, it is undesirable to have the pH maintained continually between 9 and 9.5 when this level is due to the addition of caustic wastes. Such pH conditions are entirely different from and more harmful than the naturally occurring but brief higher levels which may be as high as 10 or 10.5. These natural high pH levels are produced by photosynthesis due to the removal of CO_2 and they are always accompanied by high D.O. levels. High pH interferes with oxygen uptake of some marine and freshwater fishes and may limit their ability to survive at low oxygen tension (20). At values below 5 and above 9, the pH seriously affects the ability of some fishes to extract oxygen from the water. This ability varies with the species; with bass and crappie the pH can be lowered to almost 4 before their ability is affected (21) (22). In general, fish are able to extract oxygen best at pH levels from 7.0 to 8.5 but such fish as perch, bass, crappie, goldfish, trout, and green sunfish have a wide range of tolerance. The bluntnose minnow and one of the shiners, Notropis whipplii, were found to be very sensitive as they can extract oxygen best at pH 7.0 to 8.0 (20). Some fishes can survive rapid changes in pH. Laboratory studies (21) have indicated that goldfish withstood changes from 7.2 to 9.6, black bass from 6.6 to 9.3, and sunfish from 7.2 to 9.6. The amount of dissolved oxygen is a determining factor as to whether or not these changes can be tolerated (21).

In the range from 5 to 9.5, pH as such has not been shown to be detrimental to fishes. However, changes in this range can drastically affect the toxicity of certain materials, and they also influence the ability of fish to absorb oxygen from the water. Further, it has been noted that in the more productive streams pH usually falls in the range from 6.5 to 8.5. At pH levels above and below these values some of the essential minerals become unavailable. Thus, while pH in the range from 5.0 to 9.5 is not in itself directly harmful to fishes and this range may be used in setting up water quality criteria, from the standpoint of productivity, it is recommended that every effort be made to keep pH values in the range of 6.5 to 8.5.

Dissolved Oxygen

There are a host of environmental and other conditions which influence or determine the solubility of oxygen in water, the amount of dissolved oxygen favorable to fish life, and the minimum amount needed for existence. In fresh waters, temperature is the most important factor affecting the solubility of oxygen. Dissolved solids are rarely present in sufficient amounts to have an appreciable influence. Several environmental conditions may influence the optimum amount of oxygen required by fish or interfere with the obtaining

of oxygen by the fish or may change or increase their minimum need for oxygen. Among these are temperature, pH, CO_2, and dissolved solids.

Temperature increases within the range favorable to fish are accompanied by a progressively higher metabolic rate and a continuous increase in the oxygen uptake. Wiebe and Fuller (23) found that at 25°C. the oxygen consumption of largemouth black bass was 282 percent of that at 15°C. At 20°C. it was 177 percent of the consumption at 15°C. This is in accord with the van't Hoff law which states that for any chemical change the rate of reaction is increased between 2- and 3-fold for every 10°C. increase in temperature. Temperature is of outstanding importance in the determination of environmental requirements since the oxygen consumption increases as temperature rises whereas solubility of oxygen decreases. Because the annual range in temperature of streams of the temperate region may be as much as 28°C., oxygen consumption at peak temperatures may be several fold what it is at minimum temperatures, whereas at peak stream or lake temperatures the water will hold only about half as much oxygen as it does at minimum temperatures. Graham (24) found that for speckled trout the rate of oxygen uptake increased with increasing temperature up to the ultimate upper lethal temperature, if sufficient oxygen were available. Water containing less than 75 percent of the air saturation level of oxygen reduced the activity of speckled trout at all temperatures, and above 20°C. (68°F.) fully saturated water is required to allow the full scope of activities. Several other investigators have also found that the oxygen requirements of fishes become greater with increases in temperature (25) (26) (27).

Temperature also markedly affects dissolved oxygen concentrations which are lethal to various species of fish. Burdick (28) found that smallmouth bass died in 5 to 9 hours at oxygen concentrations of 0.7 p.p.m. to 1.17 p.p.m. at temperatures of 52°F. to 72°F. There was also some variation in the turnover time for different species of fishes. At 55°F. and oxygen concentrations of 1 to 2 p.p.m. the turnover times were as follows: brook trout, 1-3/4 hours; brown trout, 2-1/2 hours; and rainbow trout, 3 hours. At 69°F. to 71°F. these fishes turned over in approximately the same time at oxygen concentrations of 2.3 to 3.4 p.p.m.

Several other environmental factors also interfere with oxygen uptake or increase the oxygen requirements of fishes. High and low pH levels interfere with the ability of fishes to absorb oxygen from the water. High CO_2 concentrations interfere with the utilization of dissolved oxygen. Fry and Black (29) found that the common sucker, with its CO_2 sensitive blood, was unable to remove oxygen from water containing CO_2 tension which did not hinder the respiration of bullheads, the latter possessing blood with a very low sensitivity to CO_2. Under pollutional conditions fish generally require more oxygen (45) (46) (20). At low dissolved oxygen levels fish succumb to concentrations of toxic materials which they can tolerate at high dissolved oxygen levels.

Many studies have been made in attempts to determine the lowest D. O. levels tolerated by different species of fish. Gutsell (30) reported that some brook trout could endure, for a short period, an oxygen concentration as low as 1. 2 p. p. m. ; however, some asphyxiation occurred at a D. O. content of 2. 5 p. p. m. Smallmouth black bass lived for a time at 0. 4 p. p. m. D. O. Wiebe (22) found that some fish can withstand sudden wide changes in the concentration of oxygen and that they can live in water supersaturated with oxygen. The increase in D. O. was followed by a slowing down of the respiratory movements. Fry (31) states that at 49°F. the ultimate minimal tolerance of brook trout for dissolved oxygen is 0. 9 p. p. m. Gardner and King (32) reported the asphyxial level of trout to be 1. 1 p. p. m. D. O. at 6. 5°C. and 3. 4 p. p. m. at 25°C. Thompson (33) on the basis of field studies, reported that carp and buffalo lived in water having 2. 2 p. p. m. D. O. However, he found a variety of fishes only when there was over 4 p. p. m. of oxygen and the greatest variety of fishes were present when the D. O. was 9 p. p. m. He found that fish died overnight in water containing less than 2 p. p. m. D. O. Ellis reported (19) that goldfish, perch, catfish, and other species of freshwater fishes when maintained in water of constant flow, composition, and temperature (20° to 25°C.) showed respiratory compensation in both volume and rate when the dissolved oxygen was reduced to slightly below 5 p. p. m.

In addition to those environmental conditions which influence the oxygen requirement, there are several physical, chemical, and physiological conditions which influence the ability of fish to extract oxygen from the water, its need for oxygen, and its ability to resist low oxygen levels. First, it must be realized that ability to extract oxygen from the water and to resist low D. O. levels varies with the species. It is well known that dogfish, carp, and gar can survive at much lower D. O. levels than trout and several other fishes. Some fishes are more efficient in the extraction of oxygen or their blood is not as sensitive to the presence of CO_2.

The amount of oxygen required by fishes is determined in part by activity. It is generally recognized that a man lying in bed does not breathe as deeply or require as much oxygen as one digging a ditch. It has been reported that from two to four times as much oxygen is required by a fish when it is active as when it is quiescent (24) (26) (34). Under actual stream conditions a fish must maintain its position against the current, find, pursue, and catch its food, avoid its enemies, and reproduce. All these activities require oxygen in such amounts that D. O. levels at which the fish can just survive are unsatisfactory. Age, size and season are also of importance. In general, fry and younger fish have a higher metabolic rate and require more oxygen than adults (35) (36). Because of increased activity and their physiological condition fish require more oxygen at the spawning season. Studies carried out in our laboratories indicate that D. O. requirements are different at other times of the year and further, the physical condition of the fish is of outstanding importance in determining requirements and the minimum level tolerated. An actively feeding, rapidly growing fish requires considerable more oxygen than one which feeds very little. Since growth is rapid in the fry to fingerling stage it is expected that for many species D. O. requirements

will be higher at this period. Eggs deposited in bottom materials require higher D. O. concentrations than do adult fish. Since the current through the bottom materials is slow, the amount of water flowing by the eggs per unit of time is small and thus it must contain more D. O. to provide needed requirements.

Through acclimation, resistance to low D. O. levels may be increased. Fry (31) reports that through acclimation the lethal dissolved oxygen level can be reduced to about one-half the corresponding value for trout accustomed to air-saturated water. Lower dissolved oxygen levels can be tolerated for considerable periods through an increase in respiration rate and volume of water pumped, reduced activity and food consumption, and an increase in blood haemoglobin (37) (38). By means of such adaptation fishes may live for considerable periods at reduced oxygen concentrations without apparent harm. This does not mean, however, that they can complete their life cycle at such levels. Further, ability to live more or less indefinitely at low oxygen levels does not mean that some of their physiological processes have not been altered so that their well being and growth are adversely affected. It has been reported (4) that the bullhead is unable to become acclimated to increased temperature when D. O. levels are low whereas it becomes rapidly acclimated at normal D. O. levels. Dissolved oxygen levels adequate for growth, reproduction, normal activities, and well being are considerably higher than levels which can be tolerated for extended periods through acclimation and compensation.

Studies of the oxygen requirements of fishes fall into two categories: laboratory investigations, where as many as possible of the variables are controlled, the factor under study is varied, and the effects on fishes directly observed for a relatively short period; and field studies, where the variable in question is measured in different sections of the stream and is related to the fish population in various areas. Both types of study have certain advantages and disadvantages. It is very difficult to relate laboratory results to field conditions, while in the field studies, factors other than the variable in question (dissolved oxygen concentration) might have a bearing upon results. It is believed that the best approach is to carry on both laboratory and field studies so that they supplement each other. In the interpretation of laboratory findings, it must be recognized that fish are usually held under favorable conditions and it is necessary to realize that all findings are not applicable to natural conditions.

The Lytle Creek studies (40) and other field studies have indicated dissolved oxygen concentrations at which fish and their food supply can maintain themselves. Twenty-four hour studies were made on Lytle Creek at all seasons of the year at selected stations to determine D. O., CO_2, pH, and temperature. Such studies or a continuous record of dissolved oxygen are essential for investigations of D. O. requirements as there are great diurnal and seasonal variations in oxygen concentration. Fish populations and growth rate studies were made over a two-year period (41) (42) in order to relate them to environmental conditions and their seasonal variations in

in different portions of the stream. Uncontrolled variables encountered in stream studies usually make it difficult to be certain that differences in fish populations are caused by oxygen concentration alone. However, it is believed that variations in oxygen concentration were the important variable in Lytle Creek since fish appeared first in the riffles of the upper zone of recovery and were found first in the pools much farther downstream. Since fish were not present in the pool immediately below the riffles or between them, it is believed this difference is due to D. O. as other limiting factors probably would not change so rapidly. In streams having a considerable biological oxygen demand there are marked differences in D. O. in the pools and riffles. In studying a section of the Scioto River, it was found that the D. O. at the tail of a large pool was 0. 1 p. p. m. while about 200 yards downstream, water which had passed over a wide shallow riffle on one side of the stream contained 5. 6 p. p. m. oxygen. Some 20 feet from the riffle in the main flow of the river there was 2. 5 p. p. m. of oxygen.

In streams polluted with organic wastes, toxic materials such as H_2S, NH_3, and CH_4 may be formed by anaerobic decomposition. The H_2S may escape or be fairly rapidly used by certain bacteria such as Beggiotoa, Thiothrix, and Sphaerotilus (43). Usually much of the NH_3 is converted to NO_3 and both of these materials are rapidly utilized by the dense growths of algae in the recovery zone (44). Most of the CH_4, which is not very toxic, escapes as a gas. Thus, while toxic materials may be formed, it is possible that they do not exert a marked effect on the fish.

Determination of the oxygen requirements of fishes and establishment of suitable dissolved oxygen criteria are especially difficult tasks. A great many studies have been made of the oxygen requirements of fishes. Investigators have not always used a uniform approach. In fact, there has been great diversity in the species studied, the conditions under which they were studied, the experimental methods used, the objectives of the study, the caliber of the investigation, and the interpretation of results. Consequently, data obtained have varied widely and have not always been in agreement. Short time studies carried out in aquaria at low temperatures with resistant fishes which are not fed indicate only that certain fishes can survive very low concentrations of dissolved oxygen for limited periods. It should be recognized that these levels are not adequate for normal existence or completion of the life history of all the important fishes. In setting water quality criteria for the protection of aquatic life, it must be recognized that mere survival is not enough and that the minimum dissolved oxygen level should be one suitable for the continuous maintenance of a satisfactory fish crop. Minimum D. O. levels at which some species of fish can, through adaptation, resist death by asphyxiation for a time are not adequate for completion of the normal life cycle. Oxygen levels must be continuously adequate for the general well being of the fish and the maintenance of fish food organisms. Before adequate criteria can be established it is essential, therefore, to know the environmental requirements of the fishes since the objective is to provide suitable conditions for them.

Concentration of dissolved oxygen is often expressed as weekly, monthly, or sometimes daily, averages. Such values are not satisfactory as they do not indicate environmental variations and may actually be misleading from the standpoint of the continued existence of the fish. It is the extreme variations which may become limiting and which are the most important for indicating unfavorable habitats.

Some D. O. criteria have been set up as percentages of saturation. This procedure is deemed undesirable because over the range of temperature observed in our natural waters, 50 percent of saturation may mean 7.3 p. p. m. oxygen or 3.5 p. p. m. As temperature increases the amount of oxygen which can be held by the water decreases, whereas the amount required by the fish increases. It is believed that criteria for dissolved oxygen should be expressed in parts per million by weight.

Findings in Lytle Creek have indicated that in a stream section in which the oxygen concentration is usually above 5 p. p. m., the occurrence of concentrations below 5 p. p. m., but not below 3 p. p. m. for a few hours, does not have an adverse affect upon a well rounded warm-water fish population. Minnows and other coarse fishes were found in the section where minimum D. O. levels dropped to 2 p. p. m. or slightly below. On the basis of these studies and other pertinent data it is believed that for a well rounded warm-water fish population, dissolved oxygen concentrations must not be below 5 p. p. m. for more than 8 hours of any 24-hour period and at no time should they be below 3 p. p. m. For the maintenance of a coarse fish population dissolved oxygen concentrations should not be below 5 p. p. m. for more than 8 hours of any 24-hour period, and at no time should they be below 2 p. p. m.

The salmonoid fishes are not usually found in streams where minimum dissolved oxygen concentrations are lower than 4 to 5 p. p. m. For normal feeding and adequate growth at least 5 p. p. m. dissolved oxygen are required. Successful development of eggs and fry require a minimum of 6 p. p. m., while for the full range of activity for brook trout and perhaps for other members of the family, 7.6 p. p. m. are required at 15°C. and full air saturation at 20°C. and above (31). It is believed, therefore, that for good salmonoid production dissolved oxygen concentrations should not be less than 6 p. p. m.

Carbon Dioxide

Carbon dioxide may influence the toxicity of other materials or it may in itself be harmful if present in sufficient quantities. Alabaster and Herbert (48) found that CO_2 was not toxic to rainbow trout within a 12-hour exposure at concentrations up to 30 p. p. m. but was toxic at 60 p. p. m. and that period of survival decreased as the concentration increased. The presence of CO_2 in concentrations from 15 to 60 p. p. m. was found to reduce the toxicity of ammonia. Higher concentrations are toxic; 100 to 200 p. p. m. can be rapidly fatal to moderately susceptible fresh water fishes in well oxygenated water. Fifty to 100 p. p. m. can cause distress and may be lethal. Both marine and fresh water fishes vary greatly in their resistance to CO_2.

Wells (49) reports that resistance of fishes to harmful conditions varies with the species, with age or size and weight, with the condition or physiological state of the individual, and with the season. He found that practically all the fishes with which he worked were least resistant just after the breeding season--June, July, and August--and most resistant before it--March, April, May (50). Powers (51) has shown that the ability of marine fishes to extract oxygen at low concentrations was adversely affected by moderate amounts of CO_2 which lowered the pH. The investigation of Black, Fry, and Black (52) demonstrated the influence of CO_2 on the utilization of oxygen by 16 species of fresh water fishes. It was found that oxygen in the respired water at the time of death was higher when the tension of CO_2 was increased. The ability to take up oxygen in the presence of CO_2 varied with the species. Powers and co-workers found (53) that fish are able to absorb oxygen at a low oxygen tension through a wider range of CO_2 tension than is found in the natural waters in which they live. Most workers have found that naturally occurring levels of CO_2 are not detrimental to fishes. It is believed that concentrations under 30 p. p. m. in the absence of other adverse factors will have no harmful effects on most species. The majority of investigations indicate that CO_2 becomes rapidly harmful at concentrations of 100 to 200 p. p. m. Surber (54) found that concentrations between 55 p. p. m. and 78. 5 p. p. m. in hard water at pH 6. 9 to 7. 0 caused a decided increase in the loss of eyed eggs and the number of deformed trout fry. Concentrations up to 43 p. p. m. apparently had no harmful effect.

Dissolved Solids

Natural, unpolluted waters of lakes and streams have in solution small amounts of the anions CO_3^{--}, Cl^-, SO_4^{--}, smaller quantities of NO_3^-, NH_4^+, PO_4^{---}, and NO_2^-, and traces of many others. The metallic cations are Ca^{++}, Mg^{++}, Na^+, K^+, Fe^{+++}, Mn^{++}, and traces of several others. These materials exert a physiological and osmotic effect to which organisms have become adapted. In fact, these dissolved materials are required by the organisms. Rawson (55) found a positive correlation between the total solids in fresh waters and the average standing crop of plankton and bottom fauna. The type of rock formation and soil largely determines the concentration of dissolved solids in a water but erosion may be of considerable importance. Pollution may also be a factor. During the period from 1906-07 to 1934-43, the average amount of dissolved solids in Lake Erie increased from 133 to 165 p. p. m., whereas those in Lake Superior remained unchanged (56) (57).

Criteria for dissolved solids have little meaning if the purpose of the criteria is the protection of aquatic life, unless the materials to be considered as dissolved solids are specified. It is apparent that salts of Hg, Cu, Ag, Zn, Pb, and Cd will have a much different effect on fishes than will equal concentrations of salts of Ca, Na, Mg, and K. In general when total dissolved solids are referred to in relation to water quality criteria, it is the salts of these relatively nontoxic earth metals which are believed to be under

consideration. Unnatural concentrations of these salts may affect aquatic life in two ways. If the solution of salts is physiologically unbalanced, one of them may exert a direct toxic effect. If they are physiologically balanced that is, each is present in quantities sufficient to antagonize any toxic effects of one or more of the others, they may occur in such concentrations that they exert an osmotic effect. Wiebe (58) points out that the osmotic pressure that fish can tolerate depends to a large extent on acclimatization. Fish acclimated to the extremely soft waters of East Texas cannot survive when subjected to salinities to which the fish of the Pecos River are continually exposed. Texas rivers (58) range in total dissolved solids from 45 to 4,810 p. p. m. Wiebe found as much as 28,000 p. p. m. of chloride in a stream where fresh water fish were supposed to live. However, Young (59) indicates that when dissolved solids reach 11,000 p. p. m. only certain fish can tolerate them indefinitely. The ability to resist high concentrations of dissolved solids varies with the species. While some fishes move from marine to fresh water or from fresh to sea water, some species have been reported as being unable to resist concentrations above 3,000 p. p. m. Young reported that Na_2CO_3 in concentrations about 800 p. p. m. was unfavorable for catfish. Huntsman (60) reports that in the Quill lakes of Saskatchewan, which have a total solids content of 16,550 p. p. m., there is a resident fish population of somewhat limited extent. It is believed that total dissolved solids in concentrations up to 3,000 p. p. m. can be tolerated by most fishes if the materials in solution are the nontoxic earth metals and are physiologically balanced.

Chlorides

The amount of chlorides is often considered as a measure of salinity or of total dissolved solids. When dealing with sea water, which is fairly uniform and the composition of which is known, chlorides can be taken as a measure of salinity or dissolved solids. This does not hold, however, for oil field brines and other wastes. Oil field brines differ drastically from one another and from sea water and many wastes contain large quantities of salts other than chlorides.

The chloride ion as such does not have much significance from the standpoint of toxicity to aquatic life. The cation is so much more important that the chloride anion is not generally considered. This is especially true with chlorides of the heavy metals such as mercury, copper, zinc, etc. Even with salts of the relatively nontoxic earth metals the toxicity of their chlorides is evidently attributable to the specific toxicity of the cations present and not to any toxicity of the chloride ions. Since the cations vary greatly in their toxicity to fish and are governing in the determination of toxicity, it is obvious that the chloride ion content of a mixture of salts is not a reliable index of toxicity.

Physiologically balanced mixed salt solutions such as sea water may be harmful to freshwater organisms because of their excessive over-all salt content and osmotic pressure rather than the specific toxicity of any particular ions present. Provided that the salts and other substances dissolved in water

are balanced against each other so as to exclude any individual toxic effects, certain hardy freshwater fishes can tolerate waters of osmotic pressures equal to those of their own bloods and even higher for extended periods. Other freshwater fishes, however, have been reported unable to tolerate balanced salt solutions with concentrations of 2,000 to 4,000 p. p. m. It is not known whether a typical freshwater fish can complete a normal life history in water of relatively high osmotic pressure, nor is it known how osmotic pressure affects the life processes of other freshwater organisms. It is, therefore, impossible at present to define the maximal safe osmotic pressure of a freshwater environment. Presumably, the tolerable osmotic pressure entails a salt concentration far higher than the limits imposed by industrial and municipal requirements. When we are dealing only with different concentrations of a particular salt mixture such as sea salt; the composition of which is known and uniform, the chloride content of the solutions (which is easily determined) can be a useful index of osmotic strength. However, when we are dealing with mixed salt solutions of unknown and varying composition (such as oil well brines and other industrial wastes), their chloride ion content is not a reliable index of osmotic strength. For example, an industrial waste brine containing a large amount of sodium sulphate can be much more active osmotically than another brine with a much higher chloride ion content which contains only sodium and calcium chlorides. It is impossible when dealing with mixed wastes to generalize as to the relationship between chloride ion concentration and osmotic, toxic, or over-all pollutional strength. It is believed, therefore, that chloride ion criteria have no practical significance as far as aquatic life is concerned.

Fluorides

Studies at our laboratory in Cincinnati have indicated that fluoride ions do have toxic properties in their own right. Further, they appear to have a cumulative effect. In 10-day tests it was found that the TL_m value for potassium fluoride was 64 p. p. m. It is believed that for good fish production the fluoride content should not exceed 5 p. p. m.

Toxic Materials

There is a great deal of literature dealing with the toxicity of various pure chemicals to fishes. The great majority of investigators have used different approaches and have carried out their studies with a variety of fishes, using different types of water for dilution. Several compilations, reviews, or bibliographies of these studies have been made (38) (61) (62) (63) (64) (67). An examination of these papers clearly indicates that there is great variation in toxic levels reported by various investigators for selected pure chemicals. This variation is especially evident in the California report (61).

The quality of the receiving or dilution water, which is often not reported by some of those investigating toxicity, is of outstanding importance in determining toxicity of a particular material or waste. Several environmental

factors may influence toxicity, such as: temperature, CO_2, D.O., pH, alkalinity, hardness, turbidity, and dissolved materials. Certain dissolved materials may significantly affect the toxicity of a waste through their synergistic or antagonistic action or through complexation, precipitation, or other action. In the case of ferro- and ferricyanide solutions, sunlight is of importance as photo decomposition of these materials occurs with the production of toxic HCN (65). The heavy metals are considerably more toxic at low pH since they are more soluble in acidic solutions. In hard waters at higher pH they are precipitated or changed in other ways to become much less toxic. It has been found that beryllium and uranium are 60 to 80 times more toxic in soft water than in hard water (66). Ellis (38) and other investigators have found that ammonia becomes rapidly more toxic at pH values above 8.0. Calcium antagonizes the toxicity of many of the heavy metals whereas some of them are synergistic with each other and become considerably more toxic when mixed; examples are Cu and Zn, Cu and Cd, and Zn and Ni (67).

The toxicity of many of the metal-cyanide complexes is greatly influenced by pH. Doudoroff (68) has reported that fish can withstand 1,000 times as much nickel cyanide complex at pH 8 as at pH 6.5. Among the metabolites, including weak acids and bases, it is the molecule and not the ion which appears to be toxic. Thus weak acids such as HCN and H_2S become more toxic as the pH is lowered and dissociation depressed, whereas weak bases such as NH_4OH become more toxic as the pH is raised.

In general, materials are more toxic at higher temperatures and at low dissolved oxygen levels. Carbon dioxide may, through its effect on pH, render some materials more toxic or it may serve to make others less toxic. Complexation, precipitation, oxidation, dissociation, recombination, or buffering action must also be considered. The influence of water quality and other environmental factors on the toxicity of various materials has been summarized by Tarzwell (69).

The character of the receiving water can cause wide variations in the toxicity of many materials to fishes. Reference to the literature on the toxicity of specific pure chemicals is of little value for determining the toxicity of a complex waste containing these and other materials. Such an approach neglects water quality, which is of particular importance, as well as synergism and antagonism, oxidation, precipitation, complexation, and other actions which may occur in the stream and may greatly influence the toxicity of a waste in a particular stream. Numerical standards for toxicity of specific pure chemicals have little value and can be misleading. From the standpoint of industry they may be very undesirable. If a regulartory agency sets numerical criteria for the heavy metals and other substances which are to be applied over a wide area, they must be set so low that allowable concentrations are not detrimental to aquatic life under those conditions at which they are most toxic. For example, criteria for nickel cyanide wastes discharged into an acid stream would have to be set so low that the HCN formed from the wastes would not be toxic, whereas in

an alkaline stream the criteria could be much higher as an increase of one and one-half pH units from 6.5 to 8.0 decreases the toxicity of this material over 1000 times. Copper is much less toxic in hard water than it is in soft water with a low pH; variation may be as great as 200 times.

It is believed that the best approach to this problem is to make bioassays with the total waste, using for dilution, water from the receiving stream at the point where the waste is to be discharged. In this way the many variables which influence the toxicity of that particular waste in that stream are taken into consideration and safe disposal or dilution rates can be determined. With certain exceptions (some of the insecticides and other materials whose toxicity is not influenced by water quality), water quality criteria for toxic materials when applied over wide areas should not be expressed as numerical values. It is believed that a tailor-made approach should be used where toxicity of the waste can be determined for the particular receiving stream at the point of discharge. When the toxicity is determined in this way allowable concentrations for that particular situation can be expressed as p.p.m. or as dilution ratios. Such an approach also permits evaluation and comparison of the toxicity of wastes from different industries along the stream.

Summary and Conclusions

The establishment of water quality criteria for the protection of our valuable aquatic resources is a complicated and difficult problem. Since the basic objective of water quality criteria for the protection of aquatic life is to provide or preserve environmental conditions essential for the survival, normal growth, reproduction, and well being of aquatic organisms a knowledge of the environmental requirements of these organisms is essential for the establishment of such criteria. Many of the activities of man have modified the aquatic environment. Among these are deforestation, unwise agricultural practices, overgrazing, and pollution. Our aquatic resources which produce billions of dollars yearly in revenues from sport and commercial fishing are a renewable resource worthy of our best efforts for preservation.

Siltation due to erosion has been and is a major pollutant. The solution of this problem by means of erosion control must be a cooperative effort among those agencies dealing with water, soil, and other natural resources.

While all the environmental requirements for aquatic life are not now known, application of the data presently available can be used effectively in the setting up of some criteria. As more data become available existing criteria can be modified and others set up in order to meet the problem adequately.

The quality of the receiving water is particularly important in determining the effects of many wastes. Among the factors influencing the toxicity of pollutants in a particular receiving water are temperature, CO_2, D.O., pH, alkalinity, hardness, and dissolved materials. Other factors which may modify the toxicity of a waste are complexation, precipitation, oxidation, synergy, and antagonism.

In view of the many factors which may influence the effects of pollutants in different streams, it is believed that in most situations numerical criteria when applied over wide areas can be set only for temperature, D.O., and pH. With a few exceptions, such as for insecticides and certain other materials, it is believed a tailor-made approach should be used in setting criteria for toxic substances. This approach would consist of bio-assays of the waste in question, using for dilution, water from the receiving stream taken from the area into which the waste is to be discharged. Such bio-assays would take into consideration the variables which influence toxicity of that particular waste and can be used to indicate safe concentrations, or the amount of dilution required.

Criteria for settleable solids and turbidity will depend largely on local conditions and will vary with the stream and the area.

When considering large areas pH values should not fall below 5 or exceed 9.5, but for good fish production it is desirable that they be maintained between 6.5 and 8.5.

For a well rounded warm water fish population dissolved oxygen levels should not be below 5 p.p.m. for more than 8 hours in any 24 hour period and at no time should they be below 3 p.p.m. If a coarse fish population only is desired minimum levels may fall to 2 p.p.m. For good production of Salmonoid fishes a minimum of 6 p.p.m. appears to be required. However, trout can live and reproduce in waters where the D.O. content may drop to 4 or 5 p.p.m. but the survival of eggs and fry and the production is usually not so great.

It is suggested that in the northern portion of the country peak temperatures for warm water fishes should not exceed 93°F. In the southern portion of the country fish are better acclimated to higher temperatures and can withstand peak temperatures of 96°F. or higher. While trout can stand peak temperatures of 80°F. to 83°F. for short periods, best production is attained in streams having summer temperatures of 60°F. to 68°F.

Allowable concentrations of toxic complex wastes for each stream or situation should be determined by means of bio-assays and safe dilutions estimated by the use of application factors or by other means.

Literature Cited

1. Anderson, A. W., and E. A. Power
   1955. Fishery statistics of the United States for 1952. U.S. Dept. of Interior, Fish and Wildlife Service. Statistical Digest, 34, pp 1-345.

2. Anon.
   1956. National survey of fishing and hunting. A report on the first nationwide economic survey of sport fishing and hunting in the United States during 1955. U.S. Govt. Printing Office, Washington, D.C. pp 1-50.

3. Brett, J.R.
   1944. Some lethal temperature relations of Algonquin Park fishes. Univ. of Toronto Studies, Biol. Ser. No. 52, Pub. Ont. Fish. Res. Lab. No. 63, pp 1-49.

4. Brett, J.R.
   1946. Rate of gain of heat-tolerance in Goldfish (Carassius auratus). Univ. of Toronto Studies, Biol. Ser. No. 53. Pub. Ont. Fish. Res. Lab. No. 64, pp 1-28.

5. Hart, J.S.
   1952. Geographic variations of some physiological and morphological characters in certain freshwater fish. Univ. of Toronto Studies, Biol. Ser. No. 60. Pub. Ont. Fish. Res. Lab. No. 72, pp 1-79.

6. Embody, George C.
   1927. An outline of stream study and the development of a stocking policy. Contribution Agric. Lab., Cornell Univ.

7. Creaser, Charles W.
   1930. Relative importance of hydrogen ion concentration, temperature, dissolved oxygen, and carbon-dioxide tension on habitat selection by brook trout. Ecology, Vol. 11, No. 2, pp 246-262.

8. Fry, F.E.J., J.S. Hart, and K.F. Walker
   1946. Lethal temperature relations for a sample of young speckled trout, Salvelinus fontinalis. Univ. of Toronto Studies, Biol. Ser. No. 54, Pub. Ont. Fish. Res. Lab., No. 66. pp 1-35.

9. Tarzwell, Clarence M.
1936. Environmental improvement in trout streams. A problem in applied ecology. Doctorate Thesis, pp 1-238, Univ. of Michigan Library, Ann Arbor, Mich.

10. Tarzwell, Clarence M.
1932. Trout stream improvement in Michigan. Trans. Am. Fish. Soc., Vol. 61, (1931), pp 48-57.

11. Tarzwell, Clarence M.
1937. Experimental evidence as to the value of trout stream improvement in Michigan. Trans. Am. Fish. Soc., Vol. 66, (1936), pp 177-187.

12. Smith, Osgood R.
1940. Placer mining silt and its relation to salmon and trout on the Pacific coast. Trans. Am. Fish. Soc., Vol. 69, (1939), pp 225-230.

13. Taft, A.C. and Leo Shapovalov.
1935. A biological survey of streams and lakes in the Klamath and Shasta National Forests of California. U.S. Bur. of Fisheries Mimeographed Report. pp 1-36.

14. Summers, Francis and Osgood R. Smith
1940. Hydraulic mining and debris dams in relation to fish life in the American and Yuba Rivers of California. California Fish and Game. Vol. 26, No. 1, pp 1-22.

15. Irwin, W.H. and James H. Stevenson
1951. Physiochemical nature of clay turbidity with special reference to clarification and productivity of impounded waters. Bull. Okla. Agri. and Mech. College Biol. Ser. No. 4, Vol. 48, No. 4 pp 1-54.

15A. Wallen, Eugene I.
1951. The direct effect of turbidity on fishes. Bull. Okla. Agri. and Mech. College, Biol. Ser. No. 2, Vol. 48, No. 2, pp 1-27.

16. Buck, D. Homer
1956. Effects of turbidity on fish and fishing. Okla. Fish. Research Lab., Report No. 56, pp 1-62.

17. Longwell, J. and F.T.K. Pentelow
1938. The effect of sewage on brown trout (Salmo trutta). Jour. Exp Biol. Vol. 12, pp 1-12.

18. Jewell, M.E. and Harold Brown
1924. The fishes of an acid bog lake. Trans. Am. Microscopical Soc., Vol. 43, No. 2, pp 77-84.

19. Ellis, M. M.
1944. Water purity standards for fresh water fishes. U.S. Fish and Wildlife Service. Special Sci. Report. No. 2, Mimeographed, pp 1-15.

20. Wiebe, A. H., A. M. McGavock, A. C. Fuller, and H. C. Markus
1934. The ability of fresh-water fish to extract oxygen at different hydrogen-ion concentrations. Physiol. Zool., Vol. 7, pp 435-448.

21. Wiebe, A. H.
1931. Notes on the exposure of several species of pond fishes to sudden changes in pH. Amer. Microscop. Soc., Vol. 50, pp 380-393.

22. Wiebe, A. H.
1932. Notes on the exposure of several species of fish to sudden changes in the hydrogen-ion concentration of the water and to an atmosphere of pure oxygen. Trans. Am. Fish. Soc., Vol. 61, (1931) pp 216-224.

23. Wiebe, A. H. and Arno C. Fuller
1934. The oxygen consumption of largemouth black bass (Huro floridana) fingerlings. Trans. Am. Fish. Soc., Vol. 63, (1933) pp 208-214.

24. Graham, J. M.
1949. Some effects of temperature and oxygen pressure on the metabolism and activity of the speckled trout, Salvelinus fontinalis. Can. Jour. Res. D, 27, pp 270-288.

25. Chapman, W. M.
1938. The oxygen consumption of salmon and steelhead trout. Wash. Dept. Fish., Biol. Rept. Vol. 37A, pp 1-22.

26. Fry, F. E. J. and J. S. Hart
1948. The relation of temperature to oxygen consumption in the gold fish. Biol. Bull., Vol. 94, pp 66-77.

27. Wells, N. A.
1935. The influence of temperature on the respiratory metabolism of the Pacific killifish, Fundulus parvipinnis, due to size, season, and continued constant temperature. Physiol. Zool., Vol. 8, pp 318-336.

28. Burdick, G. E., Morris Lipschuetz, Howard F. Dean, and Earl F. Harris
1954. Lethal oxygen concentrations for trout and smallmouth bass. N. Y. Fish and Game Jour., Jan. pp 84-97

29. Fry, F.E.J. and E.C. Black
1938 - The influence of carbon dioxide on the utilization of oxygen by certain species of fish in Algonquin Park, Ontario. Anat. Rec. 72 (Supplement 1938):47.

30. Gutsell, James S.
1929. Influence of certain water conditions, especially dissolved gases on trout. Ecology, Vol. 10, pp 77-96.

31. Fry, F.E.J.
1951. Some environmental relations of the speckled trout (Salvelinus fontinalis). Rept. Pro. N.E. Atlantic Fish.Con.

32. Gardner, J.A. and G. King
1922. Respiratory exchange in freshwater fish. IV. Further compari of goldfish and trout. Biochem. Jour., Vol. 16, pp 729-735.

33. Thompson, D.H.
1925. Some observations on the oxygen requirements of fishes in the Illinois River. Bull. Nat. Hist. Sur., Vol. 15, Art. 7, pp 423-437.

34. Spoor, W.A.
1946. A quantitative study of the relationship between the activity and oxygen consumption of the goldfish, and its application to the measurement of respiratory metabolism in fishes. Biol. Bull., Vol. 91, pp 312-325.

35. Packard, W.H.
1907. The effect of carbohydrates on resistance to lack of oxygen. Amer. Jour. Physiol., Vol. 18, pp 164-180.

36. Privolnev, T.I.
1947. Critical pressure of oxygen in water for various ages of the young, Salmo salar. Doklady. Akad. Nauk, SSSR, Vol. 58, p 1197. Chem. Abs., 46:4,685(1952).

37. Black, E.C.
1951. Respiration in fishes. Publ. Ont. Fish. Res. Lab., No. 71, pp 91-111.

38. Ellis, M.M.
1937. The detection and measurement of stream pollution. Bull. Bur. Fish., Vol. 48, No. 22, pp 365-437.

39. Born, W.S.
1932. Ecological and physiological studies on certain aquatic angiosperms. Contrbs. Boyce Thompson Inst., Vol. 4, No. 4, pp 425-496.

40. Tarzwell, Clarence M. and Arden R. Gaufin
1953. Some important effects of pollution often disregarded in stream surveys. Proc. Eighth Ind. Waste Conf., Purdue Univ., Eng. Bull. Ser., 83: pp 295-316.

41. Katz, Max and Arden R. Gaufin
1953. The effects of sewage pollution on the fish population of a midwestern stream. Trans. Am. Fish. So , Vol. 82 (1952), pp 156-165.

42. Katz, Max and W. Charles Howard
1955. The length and growth of O-year class creek chubs in relation to domestic pollution. Trans. Am. Fish. Soc., Vol. 84 (1954), pp 228-238.

43. Winogradsky, S.
1888. Beiträge zur morphologie und physiologie der bakterien. I. Zur morphologie und physiologie der schwefelbakterien. A. Felix, Leipzig.

44. Gaufin, Arden R. and Clarence M. Tarzwell
1956. Aquatic macro-invertebrate communities as indicators of organic pollution in Lytle Creek. Sew. Ind. Wastes, Vol. 28, No. 7, pp 906-924.

45. Downing, K. M.
1954. The influence of dissolved oxygen concentration on the toxicity of potassium cyanide to rainbow trout. Jour. Exp. Biol., Vol. 31, pp 161-164.

46. Townsend, L. D. and H. Cheyne
1944. The influence of hydrogen ion concentration on the minimum dissolved oxygen toleration of the silver salmon, Oncorhynchus kisutch (Walbaum), Ecology, Vol. 25, pp 461-466.

47. Westfall, B. A.
1945. Coagulation film anoxia in fishes. Ecology, Vol. 26, pp 283-288.

48. Alabaster, J. S. and D. M. Herbert
1954. Influence of carbon dioxide on the toxicity of ammonia. Nature, Vol. 174, p. 404.

49. Wells, Morris M.
1918. The reactions and resistance of fishes to carbon dioxide and carbon monoxide. Bull. Ill. State Lab. Nat. Hist., Vol. 11, Article 8, pp 557-571.

50. Wells, Morris M.
1916. Starvation and the resistance of fishes to lack of oxygen and to KCN. Biol. Bull., Vol. 31, pp 441-452.

51. Powers, E. B.
1922. The physiology of the respiration of fishes in relation to the hydrogen-ion concentration of the medium. Jour. Gen. Physiol., Vol. 4, pp 305-317.

52. Black, Edgar C., F. E. J. Fry, and Virginia S. Blac
1954. The influence of carbon dioxide on the utilization of oxygen by some freshwater fish. Canadian Jour. Zool., Vol. 32, pp 408-420.

53. Powers, Edwin B., Howard H. Rostorfer, Lula Mae Shipe, and Theresa Hickman Rostorfer
1938. The relation of respiration of fishes to environment. XII. Carbon dioxide tension as a factor in various physiological respiratory responses in certain fresh water fishes. Jour. Tenn. Acad. Sci., Vol. 13, No. 3, (July 1938), pp 220-245.

54. Surber, E. W.
1936. Effects of carbon dioxide on the development of trout eggs. Trans. Am. Fish. Soc., Vol. 65(1935), pp 194-203.

55. Rawson, D. S.
1951. The total mineral content of lake waters. Ecology, Vol. 32, No. 4, pp 669-672.

56. Clarke, F. W.
1924. The composition of the river and lake waters of the United States. U. S. Geol. Surv. Prof. Paper, No. 135, pp 1-99.

57. Leverin, H. A.
1947. Industrial waters of Canada. Dept. Mines and Resources, Canada, Report 819, pp 1-109.

58. Wiebe, A. H., J. G. Burr, and H. E. Faubion
1935. The problem of stream pollution in Texas with special reference to salt water from the oil fields. Trans. Am. Fish. Soc., Vol. 64 (1934), pp 81-86.

59. Young, R. T.
1923. Resistance of fish to salts and alkalinity. Am. Jour. Physiology, Vol. 63, No. 2, pp 373-388.

60. Huntsman, A. G.
1922. The Quill Lakes of Saskatchewan and their fishery possibilities. Cont. Can. Biol., No. 9.

61. California Water Pollution Control Board
1952. Water quality criteria. State Water Pollution Control Board Pub. No. 3, pp 1-512.

62. California Water Pollution Control Board.
1954. Water quality criteria. Addendum No. 1. State Water Pollution Control Board Pub. No. 3, Addendum No. 1, pp 1-164.

63. Mackenthun, Kenneth M.
1952. Selected review of the literature on toxic materials affecting biological life in streams and sewage treatment processes. Wis. Comm. on Water Pollution. Mimeographed Rep. pp 1-37.

64. Doudoroff, Peter and Max Katz
1950. Critical review of literature on the toxicity of industrial wastes and their components to fish. I. Alkalies, acids, and inorganic gases. Sew. and Ind. Wastes, Vol. 22, No. 11, pp 1,432-1,458.

65. Burdick, George E. and Morris Lipschuetz
1950. Toxicity of ferro- and ferricyanide solutions to fish, and determination of the cause of mortality. Trans. Am. Fish. Soc., Vol. 78, (1948) pp 192-202.

66. Tarzwell, Clarence M. and Croswell Henderson
1956. The toxicity of some of the less common metals to fishes. Transactions of a Seminar on Sanitary Engineering Aspects of the Atomic Energy Industry held at the Robert A. Taft San. Eng. Center, Dec. 6-9, 1955, TID-7517, Part 1A, pp 286-289.

67. Doudoroff, Peter and Max Katz
1953. Critical review of literature on the toxicity of industrial wastes and their components to fish. II. The metals as salts. Sew. and Ind. Wastes, Vol. 25, No. 7, pp 802-839.

68. Doudoroff, Peter
1956. Some experiments on the toxicity of complex cyanides to fish. Sew. and Ind. Wastes, Vol. 28, No. 8, pp 1,020-1,040.

69. Tarzwell, Clarence M.
1957. The use of bio-assays in relation to the disposal of toxic wastes. Trans. Third Ont. Ind. Waste Conf. (1956). pp 117-124.